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Key Points:

- Cellulose oxygen isotope ratios of *Sphagnum* and vascular plants in peat cores were used to reveal the precipitated water oxygen isotopes
- The results showed that the climate in northern Japan was governed by the position of westerlies and the Tsushima Warm Current strength
- The climate changes affected the development of inland and marine cultures differently

Supporting Information:

Supporting Information may be found in the online version of this article.

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Impact of Climate Change on Hunter-Fisher-Gatherer Cultures in Northern Japan Over the Past 4,400 Years

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Abstract In Hokkaido, northern Japan, densely populated societies of hunter-fisher-gatherer cultures persisted over the Holocene until the 19th century. We used the cellulose $\delta^{18}O$ values of *Sphagnum* and vascular plants in peat cores from Rishiri Island to understand paleoclimate changes in Hokkaido over the past 4,400 years and discuss the impacts of climate changes on the development of the cultures. The cellulose $\delta^{18}O$ values showed multi-centennial and millennial variations, reflecting the intensity of the Tsushima Warm Current and the summer position of the westerly jet. The marine hunter-fisher cultures responded to changes in the strength of Tsushima Warm Current and coastal primary production. In contrast, the inland cultures responded to changes in the latitudinal position of the summer westerlies. This implies that human societies of different lifestyles responded differently to climate changes.

Plain Language Summary Climate reconstruction enables consideration of the relationships between climate change and human societies. Cellulose oxygen isotopes of sphagnum moss and grass remnants in peat cores indicated warmer and wetter climates during the intervals of 4,500–3,400, 2,800–2,300, and after 700 years BP, and cooler and drier climates in northern Japan at about 3,000 and during 2,200–1,000 years BP. These climate changes coincided with changes of human cultures in Hokkaido. The marine hunter-fisher cultures responded to changes in warm current strength and coastal primary production. In contrast, the inland cultures responded to changes in the latitudinal position of the summer westerlies. This implies that human societies of different lifestyles responded differently to climate changes.

1. Introduction

Understanding the impacts of climate change on human society is of central importance in environmental science because it facilitates prediction of the future of human society and mitigation of the climate impacts. Hunter and gatherer societies are assumed to have been influenced by climate change, and case studies provide knowledge about how climate change affects human society. Hokkaido, in northern Japan, was an area where densely populated societies of hunter-fisher-gatherer cultures persisted with some modifications through the Holocene until the 19th century (Text S1 in the Supporting Information S1; e.g., Abe et al., 2016; Habu, 2004; Inada, 2001; Nishimoto, 1985). In this area, the distribution of human culture shifted latitudinally on a centennial timescale (Sakakida, 2016), and an influence of climate on human society and culture has been suggested (Abe et al., 2016; Kawahata et al., 2009; Koizumi et al., 2003; Leipe et al., 2018; Shimada et al., 2004). However, this influence has not been tested thoroughly due to the absence of well-dated robust climate records based on hydrological proxies in Hokkaido.

Hokkaido is located within the range of the summer westerly jet (Figure 1) and at the northern margin where the East Asian summer monsoon carries moist air masses from the Pacific Ocean. When the westerly jet is located to the north, the southerly winds (i.e., the East Asian summer monsoon) reach northern Hokkaido, resulting in a warm and wet climate (Kawamura et al., 1998; Nitta, 1987). In winter, the East Asian winter monsoon influences Hokkaido and brings snowfall to the mountainous areas.

There is a close relationship between the position of the summer westerly jet, the East Asian summer monsoon, moisture content, temperature, precipitation, and precipitated water $\delta^{18}O$ and d-excess at the study site (Figure S1 in the Supporting Information S1; Li et al., 2017). In summer, the westerly jet shifts north, a warm and moist air mass from the Japan Sea and the Pacific Ocean occupies the study site (45°N), the $\delta^{18}O$ of precipitated water is higher, and the d-excess is lower. In winter, the westerly jet shifts south, a cold and dry air mass from Siberia

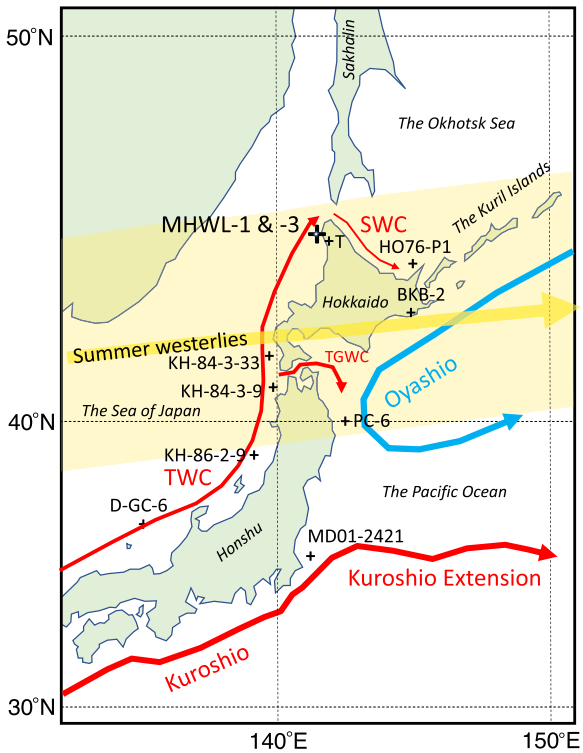


Figure 1. Map showing the locations of the study site (MHWL) and the reference sites, that is, BKB-2 (Sakurai et al., 2021), MD01-2,421 (Isono et al., 2009), PC-6 (Minoshima et al., 2007), KH-84-3-9, KH-84-3-33, KH-86-2-9, D-GC-6 (Koizumi et al., 2006), and HO76-P1 (Shimada et al., 2004), as well as the mean positions of the summer (June–August) westerly jet and the ranges of variation for the 30 years from 1988 to 2017 (yellow shade) of the summer westerlies, the Kuroshio, Kuroshio Extension, Oyashio, Tsushima Warm Current (TWC), Soya Warm Current (SWC), and Tsugaru Warm Current (TGWC). The letter "T" indicates the town of Teshio. One degree along the longitudinal line is equivalent to 96.5 km.

occupies the study site, the $\delta^{18}O$ of precipitated water is lower, and the d-excess is higher. Thus, the precipitated water $\delta^{18}O$ can be used to understand the position of the westerly jet that governed the climate of Hokkaido.

Precipitation-fed peatlands in Hokkaido contain continuous accumulations of *Sphagnum*, which are shown to be excellent archives of precipitated water $\delta^{18}O$. The $\delta^{18}O$ values of the cellulose and organic matter are potentially useful for long-term climate reconstruction (e.g., Daley et al., 2010, 2016; Hong et al., 2000, 2009; Jones et al., 2014; Kock et al., 2019; Kühl & Moschen, 2012; Sakurai et al., 2021). Recently, Sakurai et al. (2021) demonstrated that the cellulose $\delta^{18}O$ in *Sphagnum* and vascular plants in a peat core in Hokkaido reflects the precipitated water $\delta^{18}O$ in *Sphagumun* growing season (late spring to summer) and is useful for understanding atmospheric dynamics and past relative humidity.

In this study, we analyzed the cellulose $\delta^{18}O$ of separated *Sphagnum* moss and vascular plants in peat from 4.6 to 4 m-long peat cores of the Minamihama peatland. Based on the data set, we evaluated the humidity changes, summer position of the westerly axis, influence of the Tsushima Warm Current, and relationship with human history over the past 4,400 years.

2. Samples and Analytical Methods

2.1. Samples

Cores MHWL-1 (45°06'43.23" N, 141°16'14.98"E, 5 m altitude, 4.6 m long) and MHWL-3 (45°06'48.06" N, 141°16'12.13"E, 5 m altitude, 4.0 m long) were taken from the Minamihama moor, developed in a volcanic crater (Ishizuka, 1999), south of Rishiri Island in the Sea of Japan using a Russian peat sampler in June 2013 (Figure S2 in the Supporting Information S1). The presence of *Sphagnum* spores and Ericales pollen suggests the development of an ombrotrophic bog covered with *Sphagnum* throughout their peat core after 4,500 years BP, which was supplied with precipitation and sea fog (Igarashi, 2006).

The peat in this study contained subfossil *Sphagnum* remains with vascular plant stems, roots, and branches. The peat cores were subsampled every 2 cm, and the analyzed samples were selected every 10 cm. After freeze-drying, the peat was separated into *Sphagnum*, grass leaf, grass root, shrub stem, shrub branch, and shrub root fractions by picking the tissues with tweezers based on the difference in their shapes and colors. Plant species were identified by comparison with modern plant samples in the moor and with the literature (Kuwabara, 2008).

2.2. Analytical Methods

The age controls of cores were determined using accelerator mass spectrometry radiocarbon dating methods and converted to calibrated ages referring to the year 1950 using the OxCal program (version 4.4; Bronk Ramsey, 2021) and the IntCal20 data set (Reimer et al., 2020). Median values were used for the creation of the age–depth model. Cellulose was separated and purified from the homogenized tissue fraction according to the procedure of Sakurai et al. (2021). Analysis of cellulose oxygen isotopes was conducted using a continuous flow pyrolysis elemental analyzer/isotope mass spectrometer (TCEA/Delta plus XL). The average value (VSMOW) and standard deviation of duplicate analyses were used for discussion. The details of radiocarbon dating and cellulose analysis are described in Text S2 in the Supporting Information S1.

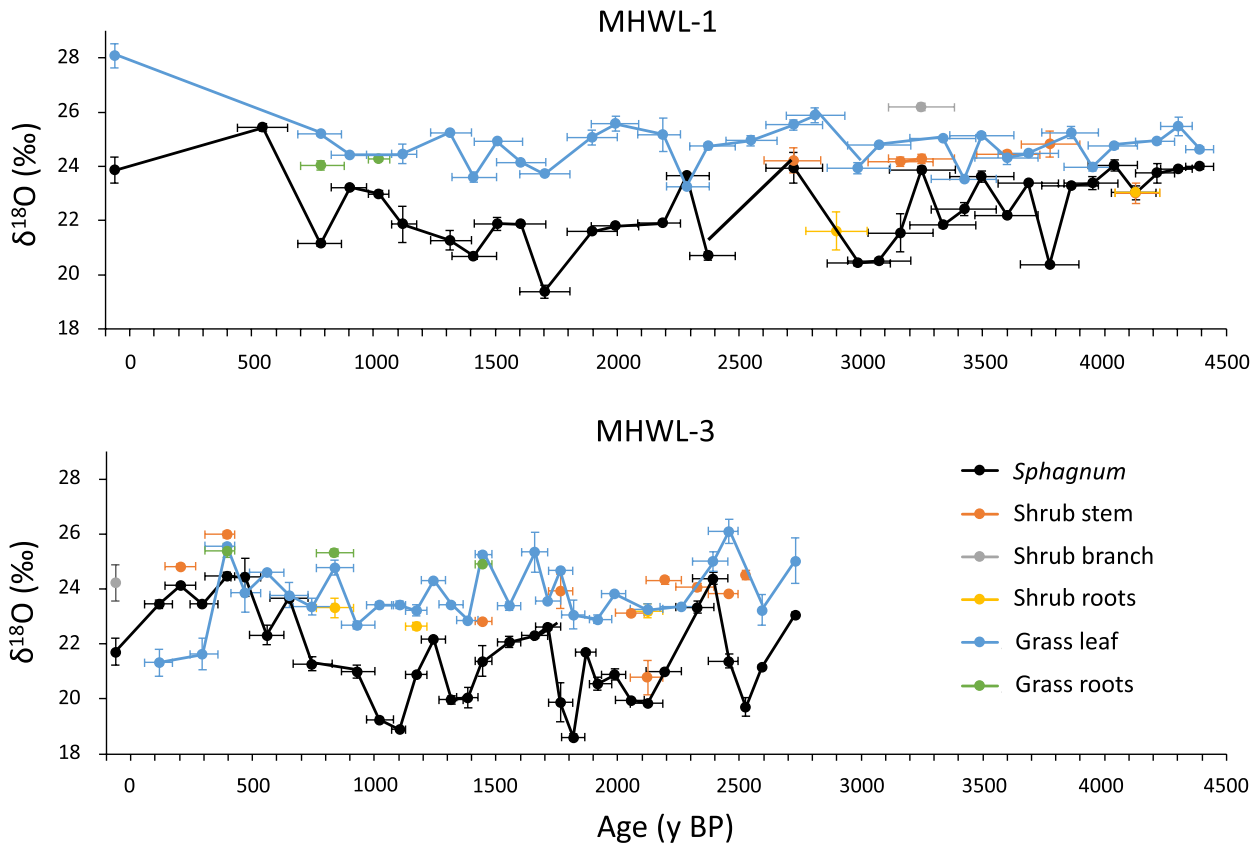


Figure 2. Changes in the cellulose $\delta^{18}O$ values of *Sphagnum* and plant tissues in cores MHWL-1 and MHWL-3. The vertical and horizontal bars of the sample value indicate the 1σ interval ranges.

3. Results

3.1. Age–Depth Model

Radiocarbon dates were measured on three and six peat samples in cores MHWL-1 and MHWL-3, respectively (Table S1 in the Supporting Information S1). The age of the core-top was assumed to correspond to the sampling year of 2013 CE (Figure S3 in the Supporting Information S1). The average sedimentation rates and the average time intervals of the samples were 0.10 cm year^{-1} and 0.14 cm year^{-1} in cores MHWL-1 and MHWL-3, and ~100 and ~70 years, respectively.

3.2. Cellulose $\delta^{18}O$

The cellulose $\delta^{18}O$ of *Sphagnum* samples varied between 18 and 25‰ and showed multi-centennial and millennial variation with higher values during the intervals of 4,500–3,200, 2,800–2,100, and after 700 years BP and lower values at approximately 3,000 and 2,000–900 years BP (Figure 2). The $\delta^{18}O$ values of vascular plant tissues ranged from 21 to 27‰ and were 2.2‰ higher on average than those of *Sphagnum* (Figure 2). Variation in the difference of $\delta^{18}O$ between vascular plants and *Sphagnum* ($\Delta\delta^{18}O_{vp-sp}$) did not depend on the differences in grass (1.5‰ on average) and shrub (1.4‰ on average) tissues (Figure S4 in the Supporting Information S1). The $\Delta\delta^{18}O_{vp-sp}$ value increased gradually from 4,500 to 2,500 years BP, was high between 2,500 and 1,000 years BP, and then decreased after 1,000 years BP (Figure S4 in the Supporting Information S1). The $\Delta\delta^{18}O_{vp-sp}$ for grass leaf was inversely correlated with $\delta^{18}O$ (Figure S5 in the Supporting Information S1).

4. Discussion

4.1. The Water Source of *Sphagnum*

In the BKB site in eastern Hokkaido, the $\delta^{18}O$ of the acrotelm water (−8.5 ± 0.4‰; Sakurai et al., 2021) that is the source water of *Sphagnum* reflects the $\delta^{18}O$ of precipitated water during its growing season, that is, May-August (−8.8 ± 1.7‰; Li et al., 2017) rather than the annual mean value. In the study site (MHWL site), we did not measure the $\delta^{18}O$ of the acrotelm water but assumed that *Sphagnum* is fueled by precipitated water during May-August (−9.9 ± 1.7‰; Figure S1 in the Supporting Information S1). The cellulose $\delta^{18}O$ values of live *Sphagnum* at the MHWL-1 and MHWL-3 sites are 23.9 and 21.7‰, respectively (Supplementary Data). Differences in $\delta^{18}O$ between cellulose in living *Sphagnum* and source water were thus 33.8 and 31.6‰, respectively, which were partly driven by the fractionation of $\delta^{18}O$ during biosynthesis (+27 ± 3‰ for C_3 plants; DeNiro & Epstein, 1979). Fractionation of $\delta^{18}O$ due to evaporation was, therefore, 5–7‰, the same as that in the Bekkanbeushi BKB-2 site (5‰; Sakurai et al., 2021). This suggests a common mechanism of preserving the $\delta^{18}O$ signal in *Sphagnum* in these two sites.

4.2. Influence of Evapotranspiration

Evapotranspiration induces enrichment of ^{18}O in the water of plant body (Craig & Gordon, 1965; Edwards & Fritz, 1986). Mosses have no stoma, uptake water passively, and lose the water through small pores by evaporation without gas and water exchange, resulting in a small fractionation of $\delta^{18}O$ during evaporation (Jones et al., 2019; Nichols et al., 2010). Vascular plants transpire water through the stomata of leaves, which enriches the leaf water in the heavier oxygen isotope. The evapotranspiration rate depends on relative humidity. When relative humidity is low, evapotranspiration is more active in both *Sphagnum* and vascular plants. However, the degree of evapotranspiration is greater in vascular plants (Jones et al., 2019; Nichols et al., 2010), resulting in a larger difference of $\delta^{18}O$ between vascular plants and *Sphagnum* ($\Delta\delta^{18}O_{vp-sp}$) under low relative humidity conditions. In the Bekanbeushi moor, since both *Sphagnum* and vascular plants use the same water source, pore water in the acrotelm layer (Sakurai et al., 2021), $\Delta\delta^{18}O_{vp-sp}$ was regarded as a potential proxy of relative humidity (Sakurai et al., 2021). Because the Minamihama moor at the MHWL sites is an ombrotrophic bog (precipitation-fed peatland) covered with *Sphagnum* and has the same hydrological conditions as the Bekanbeishi moor, we assumed that the $\Delta\delta^{18}O_{vp-sp}$ reflects relative humidity in the Minamihama moor.

$\Delta\delta^{18}O_{vp-sp}$ increased gradually from 4,500 to 2,500 years BP, was high between 2,500 and 1,000 years BP, and then decreased after 1,000 years BP (Figure S4 in the Supporting Information S1). This variation suggests that relative humidity decreased from 4,500 to 2,500 years BP and then increased after 1,000 years BP. The $\Delta\delta^{18}O_{vp-sp}$ of grass leaf was inversely correlated with $\delta^{18}O$ (Figure S5 in the Supporting Information S1), indicating the existence of a moist climate in the periods with higher *Sphagnum* $\delta^{18}O$.

4.3. Climate Factors Affecting *Sphagnum* $\delta^{18}O$

If relative humidity was the dominant factor determining *Sphagnum* $\delta^{18}O$, the correlation between *Sphagnum* $\delta^{18}O$ and $\Delta\delta^{18}O_{vp-sp}$ should be positive. However, *Sphagnum* $\delta^{18}O$ was inversely correlated with $\Delta\delta^{18}O_{vp-sp}$ at the MHWL sites (Figure S5 in the Supporting Information S1), which means that *Sphagnum* $\delta^{18}O$ mainly reflected the $\delta^{18}O$ of precipitated water rather than the effect of relative humidity, because the fractionation of *Sphagnum* water $\delta^{18}O$ is limited (Jones et al., 2019; Nichols et al., 2010; Sakurai et al., 2021).

The $\delta^{18}O$ value of precipitation in mid- and high-latitudes is related to the mean annual temperature (MAT) (0.64‰ per 1°C; Dansgaard, 1964; Jouzel et al., 1994) through exhibiting a linear relationship. The seasonal variation at the Teshio Observatory near the study site showed a linear relationship (0.17‰ per 1°C; Figure S1 in the Supporting Information S1). Sea surface and air temperature records from northern Japan over the past 2000 years show variations within 2°C (Inagaki et al., 2009; Kawahata et al., 2009; Minoshima et al., 2007; Yamamoto et al., 2021). Such a temperature change accounts for a variation of precipitated water $\delta^{18}O$ of 1.3‰, which is much smaller than the full range of cellulose $\delta^{18}O$ variation of 6.1‰ at the MHWL site (Figure 2). This implies that the temperature was not the main factor determining the cellulose $\delta^{18}O$.

The position of the westerly jet determines the $\delta^{18}O$ values of precipitated water (Li et al., 2017). The air mass north of the westerly jet has experienced heavy rainfall when it passed through the westerly jet region from

the south, resulting in depleted $\delta^{18}O$ values by 3–4‰ than south of the westerly jet (Li et al., 2017). Further, southerly winds bring moisture from the south, which induces more precipitation in Hokkaido when the westerly jet is north of the study site (Sakurai et al., 2021). This increases the $\delta^{18}O$ of peat pore water by increasing the fraction of summer precipitated water with an ~5‰ higher $\delta^{18}O$ than winter precipitated water (Figure S1 in the Supporting Information S1; Li et al., 2017). These observations indicate that the position of the summer westerly jet primarily determines cellulose $\delta^{18}O$ in Hokkaido through the processes mentioned above. When the summer westerly jet was located north, the warm air masses with more abundant moisture, with higher $\delta^{18}O$ values, reached the study site, causing heavier rainfall, resulting in greater $\delta^{18}O$ values of *Sphagnum* cellulose, and vice versa.

4.4. Climate Changes in Hokkaido Since 4,400 Years Ago

The cellulose $\delta^{18}O$ of *Sphagnum* at the MHWL sites showed multi-centennial and millennial variation with higher values in the intervals of 4,500–3,200, 2,800–2,100, and after 700 years BP and lower values at approximately 3,000 and 2,000–900 years BP (Figure 3). The variation in $\Delta\delta^{18}O_{vp-sp}$ was the opposite of cellulose $\delta^{18}O$ of *Sphagnum* (Figure 3, note that the *y*-axis is reversed). The periods of higher $\delta^{18}O$ of *Sphagnum* and lower $\Delta\delta^{18}O_{vp-sp}$ (wet climate) corresponded to periods of intensified Tsushima Warm Current (TWC) in the Japan Sea, as indicated by higher abundances of *Fragilariopsis doliolus*, a marker diatom species of the TWC, in cores KH-84-3-9, KH-84-3-33, KH-86-2-9, and D-GC-6 (Figure 3; Koizumi et al., 2006) after 2,300 years BP. The correlation between *Sphagnum* $\delta^{18}O$ at MHLW-1 and *Fragilariopsis doliolus* abundance at D-GC-6 was significantly high after 2,300 years BP (Figure 3e). This correspondence suggests that the changes in TWC strength affected the oxygen isotopes of precipitated water at Rishiri Island. However, the mechanism by which the stronger TWC could elevate the $\delta^{18}O$ of precipitated water has not been investigated. TWC water is, at maximum, 12°C warmer than the surrounding water at the same latitude in the Japan Sea and forms the warmer surface water mass in the southern and eastern Japan Sea (data from the Japan Meteorological Agency, 2021). The air masses arriving in northern Hokkaido come mainly from the Japan Sea (Li et al., 2017). We suppose that an intensified TWC formed the warmer surface water mass in the Japan Sea and may have enhanced evaporation and increased the contribution of Japan Sea-sourced moisture, resulting in the higher $\delta^{18}O$ of precipitated water and higher relative humidity.

The correspondence between cellulose $\delta^{18}O$ and the indices of the TWC was poor before 2,300 years BP (Figure 3e), suggesting that there was another factor determining cellulose $\delta^{18}O$. The variations of *Sphagnum* $\delta^{18}O$ and $\Delta\delta^{18}O_{vp-sp}$ in the MHWL sites before 2,300 years BP were consistent with SST in the Kuroshio–Oyashio transition area (Figure 3; MD01-2,421 by Isono et al., 2009). The Pacific SST at MD01-2,421 is a good indicator of the strength of the Kuroshio and its extension, which form part of the subtropical gyre circulation driven by the development of the North Pacific High (NPH; Yamamoto et al., 2004). The summer position of the westerly jet in Hokkaido is related to the strength of the NPH (Kawamura et al., 1998; Nitta, 1987) such that a stronger NPH shifts the westerly jet northward. Thus, the above correspondence suggests that the higher cellulose $\delta^{18}O$ of *Sphagnum* at the MHWL sites reflects changes in the atmospheric conditions, that is, development of the NPH, northward shift of the position of the westerly jet, and stronger influence of the East Asian summer monsoon, and vice versa (Sakurai et al., 2021).

These considerations suggest that the factors controlling climate in the study area changed around 2,300 years BP. Before 2,300 years BP, the strength of the NPH determined the climate of the entire Hokkaido area via changes in the position of the westerly jet and the East Asian summer monsoon rainfall. After 2,300 years BP, this mechanism determined the climate of eastern Hokkaido facing the Pacific Ocean (Figures 3f and 3g), but did not significantly affect the climate of Rishiri Island (Figures 3b and 3c). Instead, the intensity of the TWC determined the climate at Rishiri Island. The SST at the MD01-2,421 site showed a decreasing trend reflecting a gradual weakening of the NPH after 8,000 years BP (Figure 3h; Yamamoto, 2009; Yamamoto et al., 2004). Pollen records from Hokkaido, including the Kushu lake in Rebun Island close to Rishiri Island, show a long-term trend from a warm and moist to a cool and dry climate since the middle Holocene (Igarashi, 2013; Leipe et al., 2018), which was consistent with a gradual weakening of the NPH. This gradual weakening shifted the westerly jet south of Rishiri Island so that its position did not influence the precipitated water $\delta^{18}O$ at the Rishiri Island because the influence is optimized when the jet migrated across the Rishiri Island.

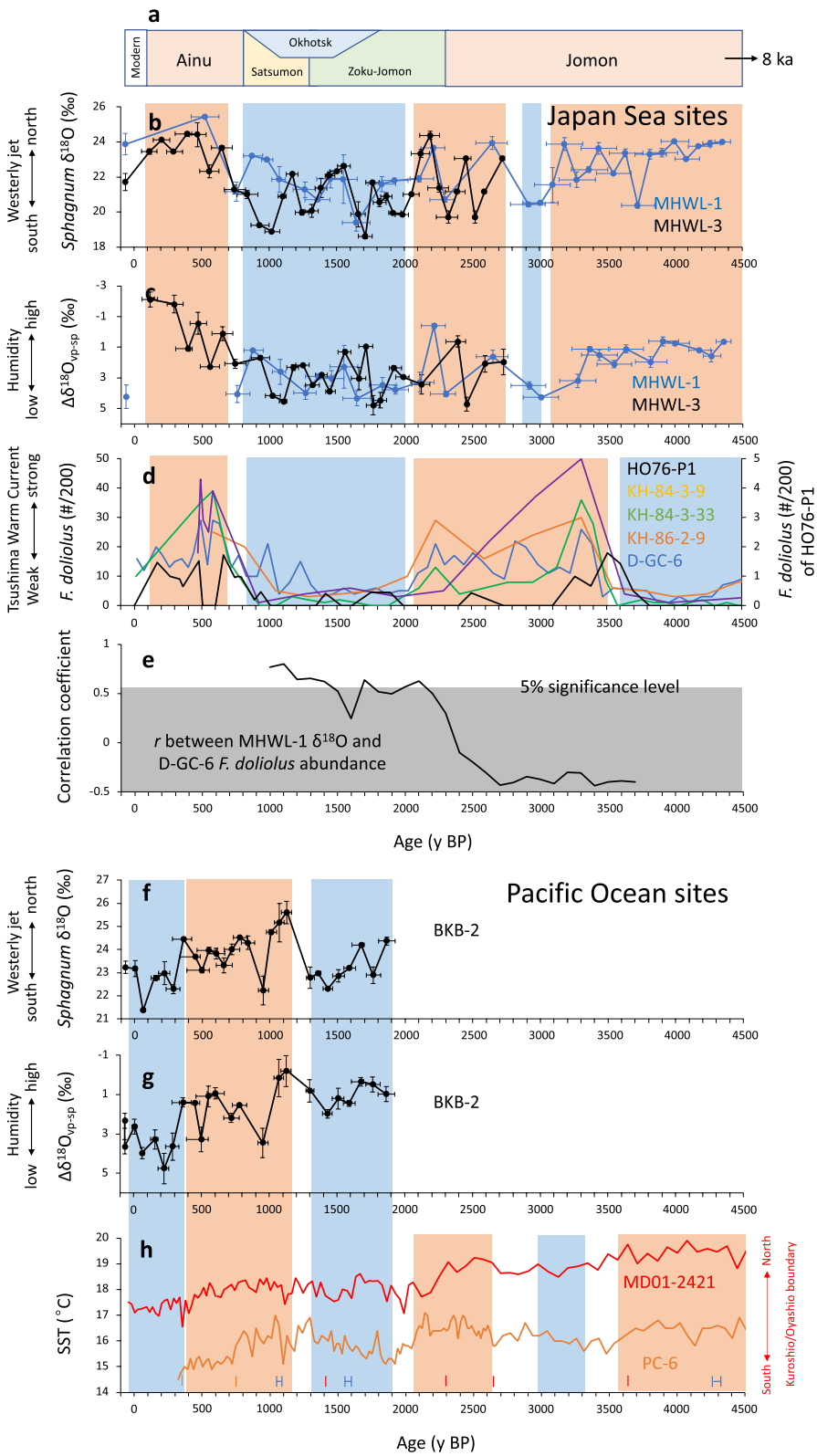

a
Modern
Ainu
Okhotsk
Satsumon
Zoku-Jomon
Jomon
8 ka
b
Japan Sea sites
MHWL-1
MHWL-3
Westerly jet
south
north
Sphagnum δ18O (‰)
c
Humidity
low
high
Δδ18Ovp-sp (‰)
MHWL-1
MHWL-3
d
HO76-P1
KH-84-3-9
KH-84-3-33
KH-86-2-9
D-GC-6
Tsushima Warm Current
Weak
strong
F. doliolus (#/200)
F. doliolus (#/200) of HO76-P1
e
5% significance level
r between MHWL-1 δ18O and D-GC-6 F. doliolus abundance
Correlation coefficient
Age (y BP)
f
Pacific Ocean sites
BKB-2
g
BKB-2
h
MD01-2421
PC-6
H
SST (°C)
North
South
Kuroshio/Oyashio boundary
Age (y BP)

Figure 3.

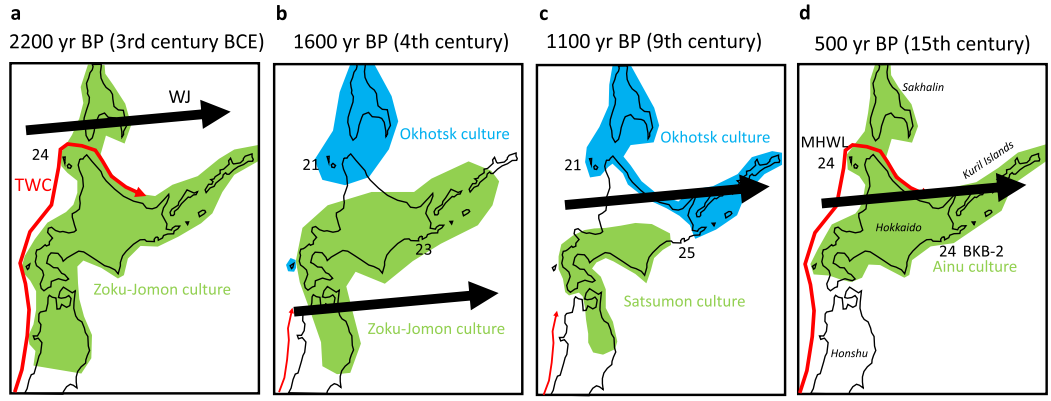


Figure 4. Schematic maps showing the distributions of the Zoku-Jomon, Okhotsk, Satsumon, and Ainu cultures (Abe et al., 2016; Sakakida, 2016) and the postulated positions of the summer westerly jet (WJ) and the Tsushima Warm Current (TWC) under different climate regimes. The numbers indicate the cellulose $\delta^{18}O$ values at the MHWL and BKB-2 sites. The positions were postulated based on the combination of the SST at site MD01-2,421 (Isono et al., 2009) and the cellulose $\delta^{18}O$ values at sites MHWL and BKB-2. We assumed that the BKB-2 value reflected the WJ, while the MHWL value reflected both the WJ and the TWC.

4.5. Climate Changes on Hokkaido and Their Relationship With Human History

The northward expansion of the Zoku-Jomon culture to South Sakhalin corresponded to the increase of *Sphagnum* $\delta^{18}O$ and the decrease of $\Delta\delta^{18}O_{vp-sp}$ at Rishiri (Figure 3), which reflected a warm and wet climate due to a northward shift of the westerly jet (Figure 4a). The southward expansion of the Okhotsk culture occurred after the climate changed to a cool and dry climate, due to both weakening of the TWC and a southward shift of the westerly jet (Figure 4b). The end of the Okhotsk culture coincided with an increase of *Sphagnum* $\delta^{18}O$ and a decrease of $\Delta\delta^{18}O_{vp-sp}$, which reflected the strengthening of the TWC (Koizumi et al., 2006) and its extension in the Sea of Okhotsk (the Soya Warm Current (SWC); Shimada et al., 2004) (Figure 3). After the TWC intensified at approximately 1200 CE under a warm and wet climate, the Ainu culture expanded northward to Sakhalin Island (Figure 4d). The above observations suggest that the evolution of cultures on Hokkaido has been affected by climate changes.

The correspondence between climate change and cultural development on Hokkaido during the last 2000 years has revealed two different types of response of culture to climate. The distribution of the Okhotsk culture (marine culture) responded to changes in the strength of the TWC and SWC (Figure 4). When the TWC/SWC was weak, the Okhotsk culture expanded along the southern margin of the Okhotsk Sea (Figures 4b and 4c). In the modern setting, along the coast, the East Sakhalin Current (ESC) flows southward in winter, and the SWC intrudes in summer (Takizawa, 1982; Ohshima et al., 2002). The TWC/SWC is nutrient-poor, whereas the ESC is nutrient-rich (Kasai et al., 2010). The weaker TWC/SWC and stronger ESC during the Okhotsk culture period may have supported high primary production and, thus, a high population of marine mammals and fishes in the coastal water, which were important dietaries for the people of the Okhotsk culture. The reentrance of the nutrient-deficient TWC/SWC water into the southern margin of the Okhotsk Sea around 1000 CE (Figure 3) may have decreased primary production in the coastal water, which reduced the population of marine mammals and fishes and forced the Okhotsk culture people to change their lifestyle to the Tobinitai culture, which was heavily influenced by the Satsumon culture.

On the other hand, the spatial distributions of the Zoku-Jomon, Satsumon, and Ainu cultures (inland cultures) stayed in Hokkaido Island, although the northern and southern margins shifted latitudinally (Figure 4). The

Figure 3. (a) History of Hokkaido and changes in (b) the cellulose $\delta^{18}O$ values of *Sphagnum*, (c) the difference of $\delta^{18}O$ between grass leaf and *Sphagnum* ($\Delta\delta^{18}O_{vp-sp}$) in cores MHWL-1 and MHWL-3, (d) the relative abundance of *Fragilariopsis doliolus*, a TWC species, in cores KH-84-3-9, KH-84-3-33, KH-86-2-9, D-GC-6 (Koizumi et al., 2006), and HO76-P1 (Shimada et al., 2004), (e) moving correlation coefficient of the 1000-year window of variations between *Sphagnum* $\delta^{18}O$ at MHLW-1 and *Fragilariopsis doliolus* abundance at D-GC-6 (resampled at 100-year interval), (f) the cellulose $\delta^{18}O$ values of *Sphagnum*, (g) the difference of $\delta^{18}O$ between grass leaf and *Sphagnum* ($\Delta\delta^{18}O_{vp-sp}$) in core BKB-2 (Sakurai et al., 2021), and (h) $U^{K}_{37}{}'$-based sea surface temperature in cores MD01-2,421 (Isono et al., 2009) and PC-6 (Minoshima et al., 2007). The bars indicate 1σ intervals. Orange (blue) shading indicates periods of higher (lower) *Sphagnum* $\delta^{18}O$ and lower (higher) $\Delta\delta^{18}O_{vp-sp}$.

northern margin of these cultures in the first millennium seems to have been passively determined by the development of the Okhotsk culture (Figure 4). The northward shift of the westerly jet around the 3rd century BCE and 15th century CE may have supported the northward expansion of the Zoku-Jomon and Ainu cultures, respectively. The southern margin after the 4th century retreated in response to the northern expansion of rice farming Yayoi cultures (Mizoguchi, 2013). This change was linked to the northward shift of the summer westerly jet (Figure 4), resulting in a warm and moist summer condition favorite for rice farming in northern Honshu. The warm and moist summer climate may have accelerated the northward expansion of rice farming cultures and the retreat of Satsumon and Ainu cultures.

5. Conclusions

The cellulose $\delta^{18}O$ values from Minamihama moor on Rishiri Island showed multi-centennial and millennial variations, reflecting the intensity of the Tsushima Warm Current and the summer position of the westerly jet. The marine hunter-fisher culture responded to changes in ocean currents and coastal primary production. In contrast, the cultures of inland hunter-fisher-gatherer-farmer cultures changed their distribution in response to changes in the latitudinal position of the summer westerlies. Their distributions seem to have been passively determined by the power balance of neighboring cultures (Mizoguchi, 2013; Nishimoto, 1985). These results imply that the human societies of different lifestyles responded differently to climate changes. Global warming is expected to shift the westerly jet northward (Shindell et al., 1999; Yang et al., 2020), suggesting future changes affecting agriculture in northern Japan. The forcing of the TWC variability remains unknown and thus the variability is unpredictable. A sudden decline of the TWC will alter the use of marine resources and the maritime culture in Hokkaido.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data are available in the Supporting Information S1 Files and NOAA's NCEI (https://www.ncei.noaa.gov/access/paleo-search/study/35393).

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